PRODUCTION OF SHORT-LIVED NUCLIDES BY SOLAR ENERGETIC PARTICLES IN THE EARLY SOLAR SYSTEM. J.N.Goswami[1,2] , K.K.Marhas[2] and S.Sahijpal[2] , [1] Lunar and Planetary Institute, Houston, Texas - 77058, USA, [2] Physical Research Laboratory, Ahmedabad - 380 009, India

Theoretical estimates for the production of the short-lived nuclides ^{41}Ca, ^{36}Cl, ^{26}Al, and ^{53}Mn by solar energetic particles have been made to check if the one time presence of these extinct nuclides in the early solar system could be attributed to their production in the nebula by energetic particles from an active early Sun. The results obtained in this study, coupled with the recent observation of correlated presence/absence of ^{41}Ca and ^{26}Al in refractory meteoritic phases [1], effectively rule out this possibility.

Several suggestions have been made to explain the presence of the short-lived nuclides ^{41}Ca, ^{36}Cl, ^{26}Al, ^{60}Fe, ^{53}Mn and ^{107}Pd in the early solar system (see [2] and references therein); these include: (i) injection of freshly synthesized stellar material to the solar nebula, (ii) "fossil" remnants locked in stardust present in the nebula and (iii) production by energetic particles either from stellar sources within a molecular cloud complex or from an active early Sun. Most of the studies done so far on the production of these nuclides by solar energetic particles (SEP) [3-6] are inadequate as they have made ad-hoc assumptions regarding the energy spectra of SEP, considered production of only ^{26}Al, ignored production by alpha particles and did not consider all the possible proton induced reactions of interest. Wasserburg and Arnould [7] incorporated alpha particle induced reactions and did a detailed calculation on the production of ^{26}Al and ^{53}Mn and found that co-production of these two nuclides by SEP to match meteoritic observation appeared to be unlikely. The recent evidence for the presence of the short-lived nuclide ^{41}Ca in the early solar system [2,8] and the strong hint for the presence of ^{36}Cl [9], led us to make a detail analysis of possible production of these two nuclides along with ^{26}Al and ^{53}Mn by SEP from an active early Sun.

We consider both the standard representations of the SEP spectra, a power law in kinetic energy ($dN/dE = \text{const.}\ E^{-\gamma}$) and exponential in rigidity ($dN/dR = \text{const.}\ \exp[-R/R_0]$). The spectral parameters γ and R_0 are assigned values of 2-5 and 50-400, respectively, which cover a wide range of spectral shapes including those seen in contemporary flares [10, 11]. The alpha particle to proton ratio was kept variable; the results presented here are for a value of 0.1 for this ratio. The cross-sections for the reactions of interest have been taken from the recent compilation by Ramaty et al. [12] for ^{41}Ca, ^{26}Al and ^{53}Mn. Measured cross sections for ^{36}Cl are not available, and we have considered nuclear reaction systematics in this mass region to obtain reasonable estimate of reaction cross sections of interest. We have considered CAI precursor nebular dust as the target material. They are assumed to be of CI composition with sizes in the range of 10μm to millimeters following a size distribution of the type: $dN/dR = \text{const.}\ R^{-\alpha}$. It may be noted that the coarse-grained CAIs, in which most of the fossil records for the presence of ^{26}Al and ^{41}Ca have been found, are devoid of solar flare heavy nuclei tracks and direct irradiation of CAIs by SEP can be ruled out. Further, the strong hint for the presence of ^{36}Cl in the early solar system comes from analysis of matrix material of a CV3 chondrite [9].

We assume the nebula to be transparent to the SEP, consider only ionization energy loss of the particles and follow the approach of Lal [10] to obtain the energy spectra of the SEP at different depths within a grain and evaluate production rates as a function of depth in grains of different sizes. The production depth profiles are then used to obtain the average production rate as a function of grain size. Using an analytical expression to represent the relation between production rate and grain size, we obtain the ensemble average production rates for different grain-size distribution with $\alpha \geq 3$. All the calculations are based on the following flux normalization : N(E>10MeV) = 100 protons $sec^{-1}.cm^{-2}$, which fairly well represents the long-term averaged SEP flux based on lunar sample data [13].

Based on the production rates for the different nuclides obtained in this study, we infer the flux enhancement factor, over the long-term averaged SEP flux noted above, necessary to match the meteorite data for the initial abundance of these nuclides in the early solar system. The initial abundance ratios considered by us are: $^{26}Al/^{27}Al = 5\times10^{-5}$ [14], $^{41}Ca/^{40}Ca = 1.4\times10^{-8}$ [2], $^{36}Cl/^{35}Cl = 1.4\times10^{-6}$ [9] and two values for $^{53}Mn/^{55}Mn$, 4.4×10^{-5} [15] and 7×10^{-6} [16], respectively. The required enhancement factor in SEP flux as a function of irradiation duration is shown in Fig. 1 for spectral index $\gamma = 3$ and R_0 = 100MV, respectively. It is obvious from the results shown in this figure that no irradiation time/enhancement factor combination can lead to co-production of ^{26}Al with any of the other three nuclides that will match the meteorite data. This is also true for the results obtained using the other values of spectral parameters considered by us. Co-production of ^{41}Ca, ^{36}Cl and ^{53}Mn (the higher initial) appears to be likely if the enhancement factor is $>10^4$ and the irradiation time scale is close to a million years; the enhancement factor will be higher for shorter irradiation duration. More importantly, the lower initial value for $^{53}Mn/^{55}Mn$ can be

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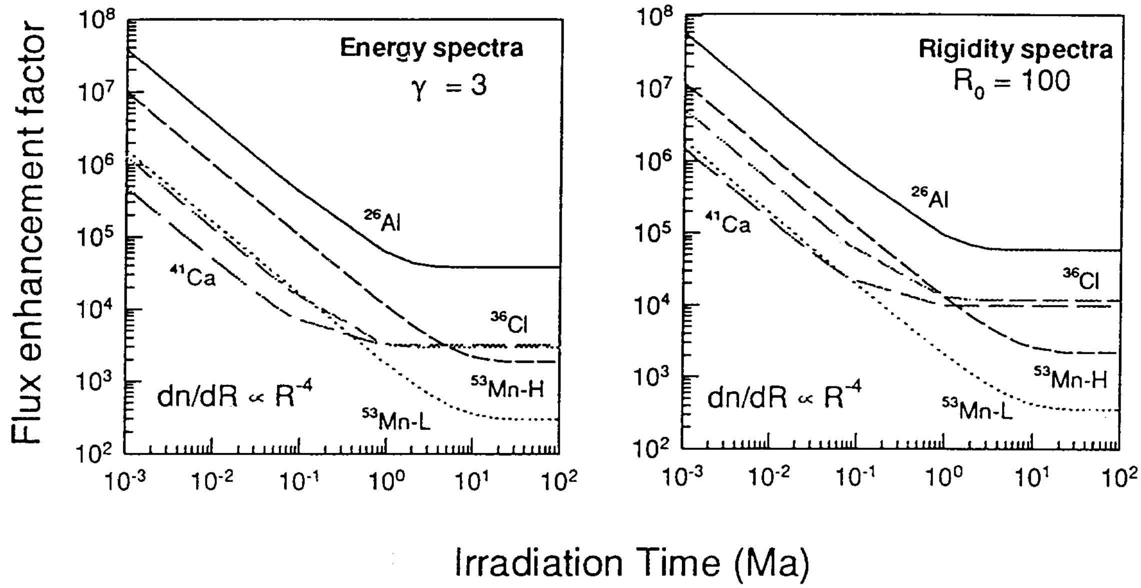

Fig. 1. Flux enhancement factor for SEP from the early Sun necessary for the production of the short-lived nuclides ^{41}Ca, ^{36}Cl, ^{26}Al and ^{53}Mn to match their abundances in the early solar system (as inferred from meteorite data), plotted as a function of irradiation duration for two spectral representation of SEP and a grain size distribution dN/dR α R^{-4}. The two values for initial ^{53}Mn/^{55}Mn ratios are labelled ^{53}Mn-H and ^{53}Mn-L, respectively.

generated even with a much lower enhancement factor for similar irradiation duration. The enhancement factors shown in this figure should be considered as lower limits as we have not considered the radial gradient in SEP flux; note that the reference flux based on lunar sample data is for irradiation at 1AU space, while the irradiation of the meteoritic phases most probably took place at a distance of 2-4AU from the Sun.

Enhancement in SEP flux from an active early Sun has been proposed to explain the observed excess of cosmogenic ^{21}Ne in solar flare irradiated olivine grains from CM chondrites [17]. These data suggest enhancement factors of ~100 to 1000, that are much lower than the values needed to explain the short-lived nuclide data. One may postulate that the enhancement factor could have been much higher at the time of irradiation of the CAI precursor solids which must have preceded the irradiation of the CM olivines. However, a crucial piece of new evidence that effectively rule out SEP production of ^{41}Ca and ^{26}Al is the correlated presence/absence of these two nuclides in meteoritic phases [1] indicating them to be co-genetic. Since co-production of these two nuclides by SEP is not possible (this is also true for energetic particle irradiation in a molecular cloud complex [12]), we can rule out irradiation scenario of any kind for the production of these two nuclides. SEP Production of ^{36}Cl also appears to be unlikely. If the lower value for the initial ^{53}Mn/^{55}Mn ratio is confirmed by further experiments, SEP production of ^{53}Mn present in the early solar system could indeed be possible.

References: [1] Sahijpal S. et al. (1996) *Meteorit. Planet. Sci. 31*,A121. [2] Srinivasan G. et al. (1996) *GCA 60*, 1823-1835. [3] Heymann D. and Dzickaniec M. (1976) *Science 191*, 79-81. [4] Clayton D. et al. (1977) *Ap. J. 214*, 300-315. [5] Lee T (1978) *Ap. J. 224*, 217-226. [6] Heymann D. et al. (1978) *Ap. J. 225*, 1030-1044. [7] Wasserburg G.J. and Arnould M. (1987) Lec. Notes on Phys. 287 (Springer Verlog), 267-276. [8] Srinivasan G. et al. (1994) *Ap. J. (Lett.) 431*, 67-70. [9] Murty S.V.S. et al. (1997) *Ap. J. (Lett.) 475*, (In Press). [10] Lal D. (1972) *Space Sci. Rev. 14*, 3-102. [11] Goswami J.N. et al. (1988) *JGR 93*, 7195-7205. [12] Ramaty R. et al. (1996) *Ap. J. 456*, 525-540. [13] Reedy R.C. and Marti K. (1991), In "The Sun in Time" (Arizona Univ. Press), 260-287. [14] Wasserburg G.J. (1985) In "Protostar and Planets" (Arizona Univ. Press), 703-737. [15] Birck J-L. and Allegre C.J. (1985) *Geophys. Res. Lett. 12*, 745-748. [16] Lugmair G. et al. (1995) In "Nuclei in Cosmos III" (AIP Press), 591-594. [17] Hohenberg C.M. et al. (1990) *GCA 54*, 2133-2140.